MIND, BRAIN, AND EDUCATION

Relational Reasoning: A Foundation for Higher Cognition Based on Abstraction

Priya B. Kalra[1] and Lindsey E. Richland[2]

ABSTRACT— This article provides an introduction to the special issue on relational reasoning. It first provides a definition of relational reasoning, and provides a conceptual framework for relational reasoning research as follows: The ability to represent concepts abstractly is critical for relational reasoning. Relational reasoning in turn provides a foundation for higher cognitive abilities such as language, and analogical reasoning. Understanding relational concepts is also crucial for STEM education. Experience, including formal education, may enhance relational reasoning ability, which in turn may facilitate future learning, forming a positive feedback loop. Creative problem-solving or reasoning can also be defined in terms of abstraction or semantic distance, providing an important link between relational reasoning and creativity. Each of the articles in the special issue is briefly discussed and framed within these concepts.

Relational reasoning is the ability to reason not just about entities and their features but about the relations among entities. Entities are objects or agents—beings or things, such "cat" or "apple." Entity concepts or categories can be identified in terms of their features (often features that are grounded in perception, such as visual or tactile features). For example, apples can be described in terms of their color, shape, texture, smell, and taste; an object can be classified as an apple or not based on its features. A cat has the features of small, furry, four-legged, and often indignant. In contrast, relational concepts and categories cannot be defined in terms of common perceptual features—in a sense, they transcend perceptual features—nor can they be defined by the specific entities involved (or their respective features). A relational concept or category is defined by the *relations* among some entities. Relational concepts range from simple spatial relations such as "above" to abstract higher-order concepts such as "mutually exclusive" or "orthogonal." Take, for example, the simple spatial relation "above"—it is not defined by perceptual features of entities, nor by the entities involved in the relation ("the apple is above the orange" is as good an example of "above" as "the airplane is above the city.") At best, relations can be defined in terms of the roles that entities play in a relation (for example, in the relation "above," one object takes the role of "higher-than" and the other "lower-than.") In this way, relational concepts are necessarily more abstract than entity categories, and therefore have the potential for application across a wide span of domains and situations.

This abstraction gives relational concepts their power, and this power is central to human higher cognition. The ability to form and use relational concepts may underpin other abilities such as planning, reasoning, and language use, which in turn can enable more complex relational thought, thereby forming a positive feedback loop (Halford, Wilson, & Phillips, 2010). Analogical reasoning, the ability to recognize common relational structures across widely different contexts, may thereby act a bootstrapping mechanism for human cognitive development, especially when combined with language, allowing greater gains than entity-based cognition alone (Gentner, 2010).

However, the abstract or higher-order nature of relational concepts and categories can also make them more difficult to learn and reason about than entity concepts. This fact becomes salient when we consider the importance of relational concepts in academic content, especially in science, technology, engineering, and mathematics (STEM) academic content. For example, much of K-12 mathematics is arguably based on understanding relational

[1]University of Western Ontario
[2]University of California

Address correspondence to Priya B. Kalra, Western Interdisciplinary Research Building, Perth Drive, London, ON, Canada; e-mail: pkalra7@uwo.ca

concepts—for example, equivalence as the underpinning of most arithmetic equations, greater than or less than, the relationship between the side of a square and its area, or what happens to x in relation to y. It has been suggested that fractions, a topic that children and adults consistently struggle with, may be difficult specifically because of their inherently relational nature (DeWolf, Bassok, & Holyoak, 2015a, 2015b, 2016; Dewolf, Son, Bassok, & Holyoak, 2017; DeWolf & Vosniadou, 2015; Kalra, Hubbard, & Matthews, 2020). For instance, when relating the numerator to the denominator, half of a pizza is the same relation as half of an hour, but no perceptual features or entity identities contribute to identifying the relation. In science, many concepts such as catalyst, predator, or force are inherently relational (Goldwater & Schalk, 2016).Recognizing this, the New Generation Science Standards (NGSS Lead States., 2013) take as a goal to move instruction of science toward considering systems of relations rather than sets of isolated topics or facts.

Understanding how people learn and use relations, then, is not only central to understanding big questions about uniquely human cognitive abilities but could be a key to unlocking more effective methods of instruction—passing on what generations of humans have learned to each new generation. Today, research on relational reasoning spans the disciplines within Mind, Brain, and Education, from rigorous computational work to neuroimaging to highly-applied classroom research. We are pleased to present examples from across this spectrum in this special issue. Together, we hope these articles demonstrate the potency of relational thought across childhood through adulthood, and highlight the positive feedback system through which the capacity to reason relationally drives gains in formal education and other cognitive skills such as creativity, and educational experience in turn drives gains in relational reasoning capacity. Below, we highlight some of the themes that weave through these articles.

ORIGINS OF RELATIONAL REASONING

To fully understand the cyclical relationship by which relational reasoning may support cognitive development and education, it is also crucial to explore the mechanisms underpinning its development. Two papers in the special issue address this aspect of the field, providing key new insights into how both experience (i.e., language inputs and schooling access) and biology (brain function) contribute to development of relational reasoning abilities.[1] An original study in this issue comes from a collaboration among researchers Frausel, Vollman, Muzard, Richland, Goldin-Meadow, and Levine. This team investigated both biological (brain injury) and environmental (low income) sources of variation in relational reasoning ability, as well as interaction between the two. The authors measured higher-order think talk (HOTT), which includes comparison, causality, and inference, in the spontaneous speech of typically-developing (TD) and brain-injured (BI) children, observed from 14 to 58 months (~1–5 years). Within the TD and BI groups, there were also differences in income. By examining *surface* HOTT and *structure* HOTT (e.g., comparison based on causality) separately, the authors were able to discern important differences across the groups. Structure HOTT requires the type of structural alignment seen in analogical reasoning and other forms of relational reasoning, while surface HOTT may be limited to, for example, comparison of perceptual features. The overall trajectories for non-HOTT and surface HOTT utterances are mostly parallel for TD and BI children, but the structural HOTT trajectories begin to diverge around 30 months and continue to grow further apart. The authors interpret these findings to mean that biological structure played an insurmountable role in children's relational reasoning talk, suggesting this variability was not likely attributable to experience or maturation alone. Similarly, income levels were clearly linked to children's reasoning skills as provided within HOTT talk, suggesting an important role for environment. When only surface HOTT was considered, the trajectories of low-income TD and high-income BI children appear to be the same, suggesting a powerful ameliorative effect of high income and a worrying damaging effect of low income; however, structural HOTT trajectories for these two groups diverge around 40 months, such that the low-income TD demonstrate continued development while BI children in both income groups appear to hit a developmental ceiling. Not only does the more abstract structural HOTT reveal these differences in group trajectories, but young children's structural HOTT has also been shown to be a better predictor of later reasoning skills than surface HOTT (Frausel et al., 2020), again underlining the importance of abstract representations.

Further demonstrating the role of formal education in relational reasoning ability, a study by Alexander and colleagues compares performance on a relational reasoning task (not limited to analogy) in educated older adults, educated young adults, and uneducated older adults. Relational reasoning ability was lower in the uneducated older adults, demonstrating that development alone cannot explain differences in relational reasoning, and suggesting a powerful potential role for formal education. In addition to the direct benefits that formal education may confer, the social and emotional sequelae of exclusion from formal education are explored. This direction of study is in keeping with the larger trend in psychology to connect cognitive, social, and affective factors.

EDUCATIONAL BREADTH OF RELATIONAL REASONING: CREATIVITY

If relational reasoning is driven by access to education, language experience, brain function, and environmental factors such as income, the other part of the positive feedback loop is to understand how these reasoning skills unfold and support reasoning in educational contexts. Importantly, two articles in the special issue explore the role of relational reasoning in building creativity, in some ways an ultimate expression of relational thought. Creativity is sometimes conceptualized as divergent thinking–that is, generation of ideas or solutions that diverge from each other and from conventional solutions to a problem. One way to operationalize divergent thinking is in terms of semantic distance. In this sense, ideas or solutions that share more perceptual features are more conventional and less creative, but solutions that share fewer perceptual features (or are further apart in semantic space) are seen as more creative. Because relational concepts can be represented abstractly, that is, with little reliance on perceptual features, there has been much interest in the potential links between relational reasoning and creativity. Accordingly, the generation of relationally similar but perceptually divergent solutions or exemplars has been used as one way to measure creativity. Two original research articles explore these potential links in this special issue, and simultaneously demonstrate the breadth of methods currently being used to investigate creativity and relational reasoning. Lundie, Harshith, and Krawczyk investigate whether stimulation of the left anterior prefrontal cortex with transcranial direct current stimulation (tDCS) facilitates analogical problem-solving, as well as whether solutions produced after stimulation indicate greater divergent thinking. Using a different approach, Dumas and colleagues[2] ask a similar question, but with acting experience (e.g., experience in theatrical productions) and the simple prompt to "think creatively" as the stimulation or intervention rather than electrical stimulation of the brain.[3] In both cases, the effect of the "stimulation" is considered in terms of the use of analogical structure as well as the semantic divergence among responses.

APPLICATIONS AND RECOMMENDATIONS

Finally, in line with the goal of *Mind, Brain, and Education* to bridge "the science of biology, brain and behavior" and its translation into "applications that will impact education," we are pleased to include in this issue two articles that work to bridge gaps within MBE and across the areas of research and practice within the field of relational reasoning.

In this issue, Goldwater, Hilton, and Davis tackle the divide between basic science research (including neuroscience research) on category and concept learning, and what is known and needed for educational research and practice. Once again, the difference between entity categories (a focus of much neuroscientific category research) and relational categories (critical for science education) is critical.

Gray and Holyoak[4] provide a synthesis of literature across the field of relational reasoning and education research to offer a cogent and accessible guide to effectively using and supporting analogical reasoning in the classroom. They distill this complex literature into five actionable principles: (1) leverage prior knowledge; (2) highlight shared structure; (3) explain the connections between semantic information and mathematical operations; (4) consider cognitive load; and (5) encourage inference generation. The authors provide both evidence in support of these principles as well as clear examples of their application. Too often, insights from the lab fail in the classroom due to a lack of the kind of implementation guidance provided by Gray and Holyoak. These types of contributions are critical if we are to reach the goal of having mind and brain research effectively serve the needs of education practice.

Informed consent was obtained for the reviewed studies.

Note: two articles for this special issue appeared in an earlier issue of MBE (15:3): Gray & Holyoak (2021) and Dumas, Dong, & Doherty (2021).

CONFLICT OF INTEREST

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

NOTES

1. Note that we are not suggesting a duality or conflict between biology-based and experience-based explanations of individual differences in relational reasoning. We know that both biology and experience can contribute to cognitive development, that biological explanations no longer need be considered deterministic, and that in fact mechanisms such as epigenetic gene-by-environment interactions provide examples of how biology (including but not limited to genetics) can interact with experience to shape performance and abilities.
2. Appeared in MBE 15:3.
3. As the authors hasten to point out, there may be some self-selection as people with certain traits or experiences may seek out acting experiences, so this study cannot assert that acting experience has a causal role in creativity, although a future longitudinal study may be able to do so.
4. Appeared in MBE 15:3.

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